Novel ophthalmoscope incorporating a double axicon

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ABSTRACT

Ophthalmoscopes are used for eye' fundus observation in medical diagnostics. The fundus is illuminated through the eye pupil and imaged to infinity by the patient's cornea and lens which act as a magnifier and allow direct observation by the physician's eye.

In currently available ophthalmoscopes the requirement of simultaneuosly illuminating and observing the fundus is met by tilting the optical axis of the illuminaton ray path with respect to the observation ray path to separate them. This also reduces the blinding effect of reflections from the patient's cornea. However by this tilt the illuminated and observed fields of the fundus no longer coincide which strongly reduces the usable field of view especially when the patient's eye pupil has a small diameter. Hence in most cases the pupil is dilated for such diagnostic check-up, which on the other hand is time consuming and very discomforting for the patient.

We avoid this drawback by using coaxial ray paths for illumination and observation. To separate them the illumination beam is expanded to a hollow-cone shape by a double axicon. The illumination beam is guided into the patient's eye by means of a 90° deflecting mirror. For fundus observation a hole is drilled in the mirror within the dark center of the expanded illumination beam. This illumination system allows application of *Köhler's* illumination principle, i. e. the light source can be imaged onto the patient's eye pupil which reduces influence of the latter on the extent of the illuminated area. This illumination principle cannot be applied in conventional ophthalmoscopes.

For practical application an ophthalmoscope with this novel illumination system offers the following advantages:
- Field of view is completely illuminated,
- pupil dilation is not necessary,
- corneal reflections do not affect fundus observation,
- illumination light losses are reduced to minimum,
- handling of such an ophthalmoscope is very convenient and easy to learn,
- ophtalmoscopy can be performed in emergency situations under severe time restrictions.

These advantages may enable ophtalmoscopic investigations in much wider fields compared to currently used illumination principles.

Keywords: Ophthalmoscopy, ophthalmoscope, eye fundus, axicon

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1. INTRODUCTION

From the observation of the eye fundus the physician can derive informations about various diseases[1]. Quick visual fundus inspection can be performed by means of a hand-held ophthalmoscope[2]. In the so-called direct ophthalmoscopy method the doctor looks into the patient's eye from a short distance of a few centimeters. The patient's cornea and lens act as an magnifier with a magnification of about 15. The doctor sees an upright image of the fundus located at infinity when both patient and doctor accomodate to infinity. The patient's pupil vignettes the field of view. To observe different parts of the fundus the physician has to change his direction of observation.

The ophthalmoscope device through which the doctor looks has no influence on the fundus imaging process described above, except that usually a lens revolver is provided in front of the doctor's eye to correct myopia or hypermetropia of patient or doctor. The main purpose of the ophthalmoscope is fundus illumination, the requirements of which are:
- sufficient brightness,
- homogeneous illuminance,
- illumination of the complete field of view,
- no disturbing reflections from the patient's cornea or from parts of the ophthalmoscope,
- no part of the illumination system should obstruct the observation ray path.

Fig. 1 shows the scheme of a conventional ophthalmoscope. A field stop is illuminated by means of an incandescent lamp (with collimation optics, not shown here). A lens or lens system projects this stop to infinity. A deflection mirror guides the light into the patient's pupil. The stop is imaged onto the patient's fundus. For special medical examinations suitable transparencies can be placed in the field stop plane, e. g. a mark for strabismal tests or a grating for size estimation of fundus details. For ophthalmoscopic examination the doctor looks over the mirror edge, i. e. the optical axes of illumination and observation ray paths are tilted against each other to separate them (*Gullstrand's* principle). The advantage of this tilt is that corneal reflections are less disturbing. On the other hand, the areas of the fundus which are illuminated and which are accessible for observation do not coincide. Only the overlapping range can be used for observation, as depicted in fig. 1, and this range gets smaller with decreasing pupil diameter (it even may completely vanish). To avoid this and to alleviate fundus observation, the patient's pupil may be dilated by means of a drug. The doctor has to wait until the drug acts, which is inconvenient for him and precludes application in cases of emergency. For the patient the drug has a very discomforting effect, as he is strongly blinded by daylight after check-up and for example not able to drive a car for several hours. Due to these problems such ophthalmic examinations are not performed very often, though they could give valuable information.

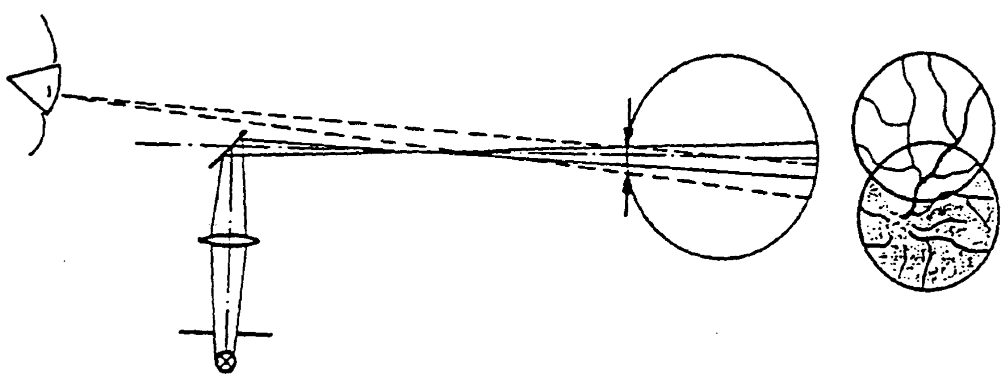

Fig. 1. Scheme of a conventional ophthalmoscope[3].
To the left the physician's eye, to the right the patient's eye. Illuminated and observed fundus areas do not coincide.

Another problem of such type of ophthalmoscope is that the deflection mirror represents a "bottleneck" for the light. To avoid light loss, the source (lamp filament) must be imaged onto this mirror or in a plane rather close to it (see fig. 1). This precludes the application of *Köhler's* illumination principle which requires the source to be imaged into the patient's pupil. In this case pupil diameter would not restrict the area of illumination. Here a small pupil has a strongly vignetting influence.

Some proposals have been made to overcome these difficulties, such as an anamorphotic illumination system[4] or an incandescent lamp with a special bow-shaped filament combined with a correspondingly shaped deflection mirror[5]. Though such ophthalmoscopes show an improved performance, the principial problems described above are not solved. The blinding effect of corneal reflections can be strongly decreased when polarizers are used in the illumination and observation path[6], however at the expense of high (more than 75%) light loss.

We present an ophthalmoscope with a hollow-cone illumination obeying *Köhler's* principle[3,7]. The illumination beam is expanded radially by means of a double axicon. Illuminated and observable areas of the fundus are coaxial, and vignetting of the illumination beam by the patient's pupil is strongly reduced.

2. THE AXICON

The axicon was introduced by McLeod in 1954[8]. Principially it is a rotationally symmetric optical element which images a point source located on its optical axis into a line image along its axis. Its most common form is based on refractive material and can be derived from a plano-convex or plano-concave lens when the spherical surface is replaced by a conical one. Fig. 2 shows such an axicon together with a focal line generated by an incident ray bundle parallel to the optical axis. This line may be real (positive axicon, as in fig. 2) or virtual (negative axicon with concave cone). Axicons may be based on the principles of refraction or diffraction; in the latter case the axicon represents a special type of holographic-optical element (HOE). They can be used to design telescopes, line projectors and autocollimators[8]. Other applications are precision aligning[9], metrology[10] and shaping of laser beams for special technical[11] and medical[12] applications. However, axicons are not widely used in optical devices.

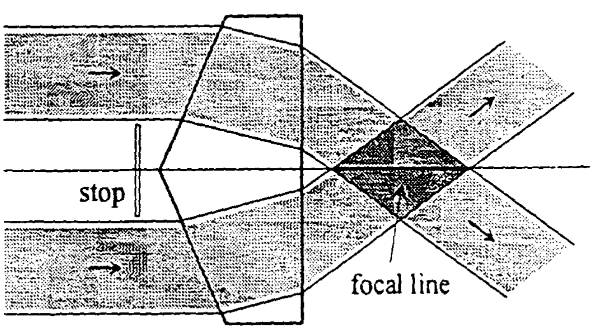

Fig. 2. Example of a positive axicon.
An incident ray bundle parallel to the optical axis generates a focal line.

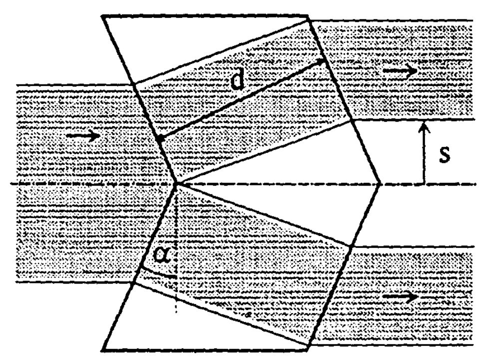

Fig. 3. Afocal double acixon.
An incident ray bundle parallel to the optical axis is expanded radially.

In our ophthalmoscope a negative and a positive axicon with the same cone angle α are combined (here in a single optical component) to generate an afocal double axicon (Fig. 3). An incident ray bundle parallel to the optical axis is expanded radially to form a ring-shaped bundle which leaves the axicon again parallel to the optical axis. The radial offset in this case is

$$s = d \sin\alpha \left[1 - \frac{\cos\alpha}{\sqrt{n^2 - \sin^2\alpha}} \right],$$

with α being the cone angle, d the distance between the cone surfaces, and n the index of refraction of the material (see fig. 3). An incident meridional ray which is not parallel to the optical axis leaves the double axicon with unchanged direction, but with another offset (as long as it hits the second cone area).

3. PRINCIPLE OF THE NOVEL OPHTHALMOSCOPE

Fig. 4 shows the optical system of the novel ophthalmoscope with the imaging ray path of the field stop. The lamp, condensor, and field stop are provided in analogy to a conventional ophthalmoscope. A two-lens imaging system which is described later projects an image of the field stop to infinity. The double axicon is situated in the telecentric range of imaging where a ray offset has no influence on the image. The deflection mirror is tilted 45° with respect to the illumination axis. An elliptical hole with a half axes ratio of $\sqrt{2}$ (here 2.1 mm and 1.5 mm) is drilled into it with such an oriention that its projections in the directions of illumination and observation appear circular. The double axicon expands the beam to a ring-shaped area around this hole. The patient's eye generates a sharp image of the field stop on its fundus.

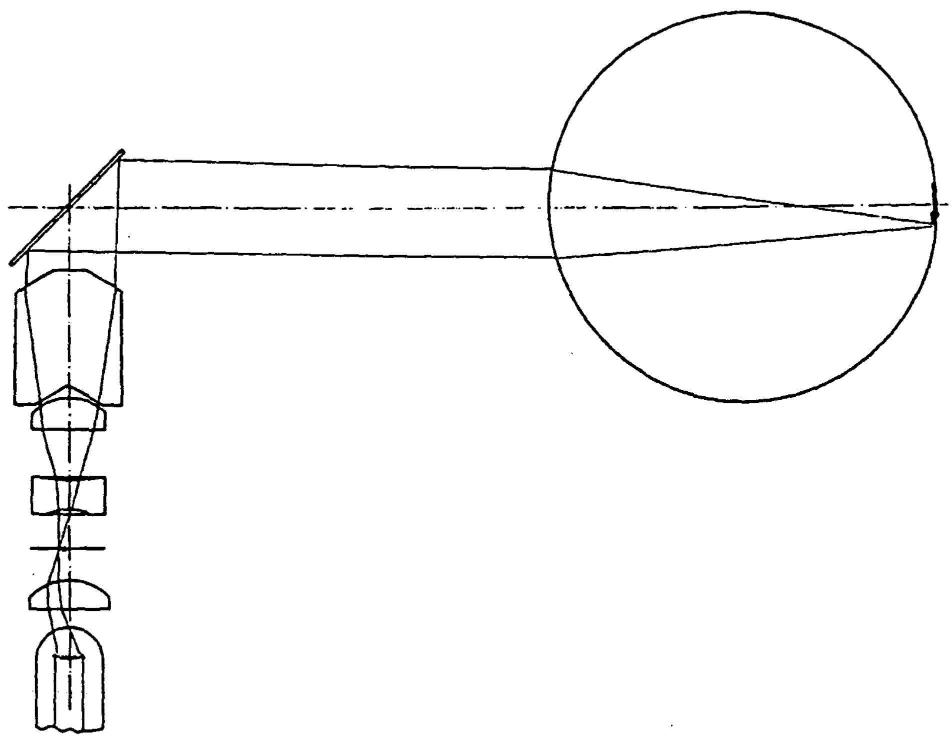

Fig. 4. Optical system of the novel ophthalmoscope with imaging ray path of the field stop[3].

The second task of the imaging system is imaging of the source. As the condensor lens projects the lamp filament to infinity, its image is formed in the back focal plane of the two-lens system, which must coincide with the patient's eye pupil, according to *Köhler's* illumination principle. The focal length of the system of 12 mm is determined by geometrical constraints (maximum allowable length of the optical system, size of the field stop and the required viewing angle). On the other hand, the patient's pupil is located about 20 mm behind the deflection mirror. Thus a retrofocus system is needed, the principal planes and focal points of which

are shifted towards the image space. After Gaussian design this two-lens system (focal lengths -6 mm and +7.4 mm) was optimized for the field stop image by means of an optical design programme (Kidger Optics). It turned out that three conic aspheric surfaces are necessary to obtain a sufficient image quality. Accuracy of these surfaces must be within a few micrometers. This optimization was calculated without the axicon, as the design programme did not allow to include cone surfaces. In source imaging the rays entering the axicon are not telecentric but convergent, thus the image is spread along the optical axis. However, image quality is not crucial here, and the aim of concentrating most part of the the light into the pupil area is easily reached.

Up to now, only meridional rays passing the axicon were considered. However due to the finite source size, aberrations of the condensor lens and and diffraction at the field stop (or another transparency situated in this plane) sagittal rays also exist. They generate an astigmatism-like aberration[13] which deteriorates image quality. Thus illumination aperture should be sufficiently small, condensor aberrations should be minimized and the spatial frequency spectrum of the object structure should be limited. The transparencies mentioned above which are used for special medical examinations must be adapted to this constraint[14].

A prototype ophthalmoscope was fabricated, the axicon ($\alpha = 30°$, $d = 6$ mm, $s \approx 1$ mm) and imaging lenses of which were made from PMMA diamond-turned on a precision lathe. For serial production these parts could be injection-molded which is possible with the required accuracy. The condensor lens (BK7 glass) is spherical with a focal length of 2.5 mm. In spite of its large spherical aberration image quality of the field stop is sufficient.

4. CONCLUSIONS

We introduce a novel ophthalmoscope with coaxial ray paths for illumination and observation. The illumination beam is expanded radially into a hollow-cone shape by an afocal double axicon. This illumination system allows application of *Köhler's* illumination principle, i. e. the light source can be imaged onto the patient's eye pupil which strongly reduces influence of the latter on the extent of the illuminated area and reduces illumination light losses to minimum. Illuminated and observable areas of the fundus are coaxial, thus pupil dilation is not necessary, which enables ophtalmoscopy to be performed even in emergency situations. Handling of such an ophthalmoscope is very convenient and easy to learn.

Further improvements include
- lens system optimization including the axicon,
- the use of a specially designed aspheric condensor lens.

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